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RESEARCH REPORT 114

Contract No. AF 04(647)-278

August 1959

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by

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ABSTRACT

Turbulent pipe flow experiments have been obtained under conditions which were similar to the peak heating conditions of high performance ballistic missiles (approximately 20 percent lower enthalpy and one-half the stagnation pressure). Several typical ablation materials were investigated to determine their performance under these conditions. It was possible to determine the effective heat of ablation for each of these materials and to experimentally demonstrate the difference between the ablative process in laminar and turbulent flow. In this paper the Teflon experiments are discussed in detail to demonstrate the validity and power of this technique.

SYMBOLS

B	defined by Equation (10)
c_p	specific heat
D	inside pipe diameter
f	fraction of ablated material which vaporizes
h	enthalpy or energy per unit mass
h_v	heat of vaporization
$(\Delta h)_o$	enthalpy difference across boundary layer
$H^{(o)}_{eff}$	effective heat of ablation, excluding radiation emission
H_{eff}	effective heat of ablation including radiation emission
L	length
ℓ	$\rho\mu$ ratio across boundary layer
m	mass
$\dot{m}$	mass rate
M	molecular weight
n	exponent defined by Eq. (2) or Eq. (3)
q	heat transfer rate
RT_o	reference energy, 33.86 Btu/lb
R	inside pipe radius
R_e	Reynolds number, $\rho uD/\mu$
t	time
T	temperature

U	gas velocity
x	percent phenolic
β	transpiration factor
ϵ	emissivity
μ	viscosity
ψ	ratio of heat transfer, with and without, mass injection
ρ	density
σ	Prandtl number

SUBSCRIPTS

av	average
cw	cold wall
f	final
i	initial
j	with injection
ℓ	laminar
m	material
rad	radiation
s	stagnation
t	turbulent
v	vapor
w	evaluated at wall

Introduction

The problem of dissipating large quantities of heat by ablation has received considerable attention in the literature during the past few years. Ablation is presently the favored method of handling the re-entry heating problem for ballistic missile nose cones. It is being considered for use in large rocket nozzles and is one of the methods of protecting satellites from aerodynamic heating during re-entry.

A considerable amount of theoretical and experimental work on this subject has been published [1,2,3,4]. The theoretical understanding of the ablation process in pure materials, such as quartz-like substances, has reached a high degree of sophistication [5,6]. Combination of theory, experimental and flight test results have produced gratifying results [7,8]. However, all this work with the exception of the flight tests, has been restricted to the laminar ablation process. From a look at the Reynolds number-heat transfer history of a high performance ballistic missile nose cone, it can be seen that 95% of the material ablated from the body is lost in a turbulent flow region.

The ablation process in a turbulent flow is considerably different from laminar ablation. This is particularly true for those materials which depend on vaporization for obtaining their high values of effective heat of ablation. Qualitatively, this difference is the relative effectiveness of the vaporized material in altering the boundary layer profile in such a manner as to reduce the temperature gradient at the surface, i. e., heat transfer. In a laminar flow the injected material is very effective in producing lower gradients at the surface. However, in turbulent flow, with its fuller boundary layer profile and its turbulent motion closer to the body, the injected material is far less effective.

Turbulent ablation is sufficiently different so that experiments need to be performed in support of the theoretical predictions. To date no significant laboratory experiments have been performed where both the Reynolds number and the gas enthalpy were high enough to produce turbulent ablation. To fill this gap in our knowledge, the large high pressure arc plasma generator was developed. Still the requirements of duplicating both the flight enthalpy and Reynolds number of high performance nose cones coupled with the requirement of geometric scaling required arc facilities beyond the present state of the art. To this end large high pressure arc facilities have been developed [9].

By relaxing the requirement of geometric scaling, one is able to design significant experiments at power levels which are practical with presently available plasma generators by utilizing a turbulent pipe flow as the test media. It takes less power (and Reynolds number) to produce a turbulent pipe flow than it does to produce a turbulent boundary

layer flow. The inside of a pipe, through which the plasma is streaming at a slightly subsonic Mach number, appeared like a reasonable simulation of the flight situation. Hypersonic turbulent flow has been shown to be similar to incompressible flow both in the shock tube[10] and in hot wind tunnels[11]. The effect of pressure gradient is diminished in turbulent hypersonic flow due to the large density ratio across the boundary layer. The flat plate incompressible flow is a good simulation of the hypersonic flow situation. The inside of the pipe or pipe flow is most certainly a good approximation to the flat plate case. Thus the pipe flow experiment was initiated with the purpose of first establishing the validity of and evaluating this technique for hypersonic simulation and to produce meaningful results on the process of turbulent ablation. This paper describes this experimental technique, gives some results and discusses their significance in view of the analytical understanding of ablation.

Turbulent Pipe Experiments

Consider the subsonic flow in a pipe just aft of the plenum chamber of a high pressure arc. A sonic exit nozzle at the aft end of the pipe, in conjunction with the regulated air supply controls the pressure level in the pipe. In this pipe either fully developed turbulent pipe flow (at Reynolds numbers above about 10,000) or a turbulent boundary layer (at Reynolds numbers above 500,000, as long as the boundary layer thickness is less than half the pipe diameter, $\delta/D = .500$) can be developed. The flow in such a pipe is a reasonable representation of turbulent hypersonic flow due to the fact that in hypersonic turbulent flows the incompressible flat plate relationships appear to be applicable[10]. Of course, pipe flow is only a special case of flat plate flows.

The difficulty with pipe flow ablation experiments is the changing pipe specimen diameter with time due to ablation and the resulting changes in heat transfer. Some rough limits can be established for this type of experiment due to this effect. The energy flux in the pipe is the mass flow, ρuA, times the enthalpy, h_s, or

$$E = (\rho u A) h_s \tag{1}$$

The heat of ablation, H_{eff}, is defined as

$$H_{eff} = \frac{q}{\rho_m \, dR/dt} \tag{2}$$

where ρ_m is the density of the material to be ablated. The turbulent heat transfer rate was given in Ref. 10 as

$$q = .029 \frac{u}{L} R_e^{.8} \Delta^{-2/3} \Delta h \tag{3}$$

If you are willing to tolerate heat transfer rate changes as great as a factor of two during a given experiment, i.e., $q_{final} = q_{original}$, then the diameter change of the model specimen in terms of D_f/D_o must be no larger than 1.47. A limitation for pipe flow experiments can be established from a combination of the above equations. To obtain quantitative limits, values of the density and heat of ablation of the model material must be assumed. For a material with a specific gravity of two, a heat of ablation of 5000 Btu/lb, and a testing time of 10 seconds, the heat transfer rate which will give the limiting diameter change in 10 seconds can be plotted against energy invested in the air. Figure 1 was drawn for a pipe with a flow Mach number of 0.5. It can be seen that somewhat marginal experiments can be performed in Model B (i.e., less than one megawatt of power in the gas). In the multiple arc generator, pipe experiments can be performed at the realistic heat transfer rates of 1 - 2 KW/cm^2.

The foregoing discussion assumed utilizing the pipe as a fully developed turbulent pipe flow. To create such a flow requires Reynolds numbers based on diameter of about 10,000 and a pipe length of 15 to 20 diameters. The long pipe needed to produce the pipe flow extracts a significant amount of energy out of the gas and consequently the enthalpy level is reduced. With a large, high pressure plasma generator, as described in this paper, sufficiently high Reynolds numbers can be achieved to have actual transition and a turbulent boundary layer before the boundary layer fills the pipe.

Calculation of the conditions in pipes are supplied with hot plasma by the arc generator described in Ref. 9 are shown in Fig. 2. It can be seen that assuming transition occurs at or before a Reynolds number of 0.5×10^6 (based on the length from the plenum chamber) that a region is available in which a turbulent boundary layer, which has not yet completely filled the pipe, exists. This point is indicated by $\delta/D = .500$ or the line labeled "Fully developed pipe flow." The conditions under which the pipe diameter will change by a factor of 1.47, i.e., $q_f/q_o = 2.0$ are also shown. It is not considered to be practical to operate above this line.

The turbulent pipe flow test is not an ideal experiment for studying the details of the turbulent ablation process. However, it does offer a convenient method for evaluating ablating materials under turbulent

boundary layer conditions. Most important, it can be performed at power levels which are high but not, economically or otherwise, infeasible.

Experimental Procedure

Air stabilized arc plasma facilities have been described in detail in the literature both from the point of view of operational capability and as a tool for ablation measuring techniques[9,12,13,14]. The plasma facility used for the present experiments was described in Ref. 9, and is schematically shown in Fig. 3. The facility consists of a carbon cathode, a water-cooled anode, settling or plenum chamber, transition section, pipe test section and a sonic exit nozzle. The arc burns inside the anode (or the first nozzle) and is stabilized by tangential air injection. The hot plasma passes from the arc into the plenum chamber where unsteady effects are averaged out, into the transition section and through the pipe at a slightly subsonic Mach number and finally it exhausts to the atmosphere through the second or sonic throat.

The pipe section serves as the test section for the present experiments. In order to determine the gas properties of the plasma in the pipe for a given test, an energy balance for the entire system is maintained. Water calorimetry measurements are obtained for all sections of the arc prior to the pipe test section. Separate measurements are performed to determine the heat transfer rate in the pipe by replacing the ablating specimen with a copper water-cooled section. At identical conditions this calorimeter section is replaced by the ablating material under consideration.

During ablation, the inside diameter of the pipe increases with time due to the ablation and as a result the heat transfer rate to the pipe decreases. To check the relationship between the heat transfer rate, pipe diameter and the relative size of the pipe and the entry section, calorimetry experiments were performed. Pipes were sized to have inside diameters less than, equal to, and greater than the exit diameter of the transition section. This diameter was held constant for all tests. It was possible from calorimetry measurements to calibrate the facility, to establish the existence of turbulent flow and to evaluate the effect of pipe diameter change on heat transfer rate.

The arc facility was powered from a 1.5 megawatt capacity battery bank. In the present experiment the power in the plasma at the entrance of the pipe test section was determined to be of the order of 0.7 megawatt. It was possible to test ablation specimens under conditions which were similar to peak heating conditions of high performance ICBM (approximately 20 percent lower enthalpy and one-half the stagnation pressure). Each material was tested at a given operating condition repeatedly for various lengths of time to establish the variation of pipe diameter with time.

The materials tested during the present investigation were typical re-entry ablaters. In addition to the typical heat shield materials, tests were made using Teflon which is not suited to this type of re-entry. These tests were made to study the effect of turbulent blowing and to help evaluate the difference between the performance of the other materials in laminar and turbulent flow. The Teflon experiments were particularly useful as verifications of this technique of ablation testing and will be discussed in detail in this paper.

Data Reduction

The expression for the heat transfer rate for a fully developed turbulent pipe flow can be written as [15]

$$q = \frac{.023\,\rho u (\Delta h)_o}{\Delta^{2/3}\, Re^{.2}} \qquad (4)$$

where $(\Delta h)_o$ is the difference between the stagnation enthalpy and the gas enthalpy at the wall temperature and all the properties such as density ρ, velocity u, and Reynolds number Re are based on average properties.

For identical conditions of mass flow and power in the gas the effect of pipe diameter on the heat transfer rate is from Eq. (4),

$$q_i / q_f = (D_f / D_i)^{1.8} \qquad (5)$$

The results of the calorimetry experiments are shown in Fig. 2. Measured values of heat transfer rates to pipes of three different internal diameters are shown as a function of the power in the air as determined from an energy balance. The experiments are performed at constant air mass flow. The results for the 0.55 and 0.75 inch inside diameter pipes are adequately predicted by Eq. (1). Furthermore, the variation of the heat transfer rate with pipe diameter is predicted by Eq. (5). This result appears to be valid to the point where the test section diameter is equal to the transition section exit diameter. For cases where the pipe section is larger than the entry (a stepped entry section), Eq. (4) does not predict the data. The step in the entry section produces vorticity which increases the heat transfer rate to the pipe immediately downstream of the step to values greater than those predicted for turbulent pipe flow, Eqs. (4) and (5). The variation of

heat transfer rates for a stepped configuration can be empirically represented within the accuracy of the data as

$$q_i/q_f = (D_f/D_i)^{0.20} \tag{6}$$

The agreement of the results of the calorimetry with Eq. (1) indicates that turbulent pipe flow was achieved during the present tests. The transition section has an L/D of 8 and transition to turbulent pipe flow is apparently achieved in this section. Furthermore, the importance of establishing the variation of heat transfer rate with changes in pipe diameter is demonstrated by the effect of the entrance step as given by Eq. (6). The effect of change in pipe diameter can be reduced by the use of a facility capable of delivering a larger amount of power to the air and one which consequently can accommodate larger sample sizes. Such a facility has been developed [9] and allows turbulent pipe tests to be undertaken with small heat transfer variations, small corrections, and consequently much more accuracy.

To establish the effective heat of ablation of the various materials about ten samples of each material were run at reproduced conditions (plus or minus 5 percent in enthalpy) and the weight of each specimen was measured before and after the test. The weight of material ablated during the test is

$$-d_m = 2\pi R\, dR\, \rho_m L \tag{7}$$

where the negative sign indicates a loss of material with an increase in pipe radius. Integration of Eq. (7) between the initial and final conditions results in the following expression

$$R_f/R_i = \sqrt{1 + \frac{(m_i - m_f)}{\pi R_i^2 \rho_m L}} \tag{8}$$

From the measurement of the weight loss during the test and use of Eq. (8), the radius change of the specimen was calculated. This value represents an average pipe diameter of the specimen after the test. Several samples were sectioned and measured in detail to determine the change in pipe radius as a function of axial distance along the pipe. The values calculated from Eq. (8) were compared and found to adequately represent true average pipe radius. The effective heat of

ablation without reradiation* can be written as

$$H_{eff}^{(o)} = \frac{q}{\rho_m \, dR/dt} = (q_{cw})_{AV} \left(\frac{h_s - C_p T_w}{h_s}\right)_{AV} \frac{1}{\rho_m \, dR/dt} (D/D)^n \quad (9)$$

Experiments were conducted for different exposure times so that for each of the materials tested a curve of radius change with time could be drawn. Conditions were controlled so as to result in reproducibility from run to run within approximately 5 percent. The cold wall heat transfer rate to the pipe section was determined from the calibration curves, Fig. 2. Since there were slight variations of power in the air at the test section, i.e., the enthalpy, the cold wall heat transfer rate values for a given material test sequence were averaged. The average value of the stagnation enthalpy was also used. In order to correct the cold wall heat transfer rate, q_{cw}, to the wall temperature during ablation, the surface temperature of the ablating material was needed. It was not possible to measure this temperature during the present investigation. However, the vaporization temperature of quartz as a function of pressure[16] indicates that at a pressure of 10 atmospheres a wall temperature of 6400°R should be expected for quartz-like materials. During ablation, materials flow before evaporating and tend to reduce this temperature somewhat. Theoretical calculations by Hidalgo[8] indicate temperatures of the order of 5800°R in the nose region under conditions similar to the present experiments. As a result, the wall temperature for the present tests was assumed to be 6000°R for all materials except Nylon Phenolic and Teflon, both of which will be discussed separately in a later section of this paper. This temperature was used to perform the hot wall heat transfer correction, $(h_s - CpTw)/h_s$.

A typical plot showing the variation of radius with time (curves are for Teflon tested at two different values of enthalpy) is shown in Fig. 3. The curvature of the trend of the data is due to the change in radius and, hence, the heat transfer rate with time. The local slope of the curves and local radius were determined for discrete time intervals. These two values complete the data needed for Eq. (9). The local slope is dR/dt and the local diameter change determines the ratio of the initial to instantaneous diameter needed to correct the heat transfer rate for diameter changes. The exponent used was determined from either Eq. (5) or (6), depending upon the initial radius of the specimen. In this way, the value of the effective heat of ablation was determined for each of the materials and at several enthalpy levels for some materials.

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* The effects of radiation in this experiment are discussed in the next section.

Discussion of Results

Before discussing the results of these experiments, let us consider the difference between the laminar and turbulent ablation processes. It is now generally accepted that the value of a material as an ablative heat protection system is measured in terms of its effective heat of ablation, i.e., the heat transfer or energy absorbed per unit mass of the ablating material.

For the case of a subliming material, one which goes directly from the solid to the gaseous state (or one which forms a liquid all of which vaporizes) the effective heat of ablation can be written (from Adams[1]),

$$H_{eff} = \frac{q}{\dot{m}_v} = \frac{C_p T_w + h_v + \beta (\Delta h)_o}{(1 - q_{rad}/q)} \tag{10}$$

where $q_{rad} = \epsilon \Delta T_w^4$

The first term in Eq. (10) is the energy absorbed by the heat capacity of the material as it is heated to the temperature of the solid gas interface, T_w. The second is the heat of vaporization of the material. The third term represents the effect of blowing by the vaporized material as it enters the boundary layer. It is the only boundary layer parameter in Eq. (10) and consequently the only one which can be affected by transition. The transpiration factor, β, depends on the relative molecular weights of the vaporized ablating material and the working medium, i.e., air. Because it is a boundary layer effect, it has a different value for laminar and turbulent flow. The denominator $1 - q_{rad}/q$ represents the effect of re-radiation from the hot ablating surface to the gas.

For a non-subliming material, i.e., one which has a liquid phase before it vaporizes, Eq. (10) can be rewritten

$$H_{eff} = \frac{C_p T_w + f h_v + f\beta (\Delta h)_o}{(1 - q_{rad}/q)} \tag{11}$$

where f now represents the fraction of the ablated material which vaporizes while 1-f remains a liquid and flows off the body.

The difference between laminar and turbulent ablation can be seen from a consideration of the transpiration parameter β. By considering the data of Baron,[17] Pappas,[18] and Rubesin,[19] Hidalgo[8] has established correlations for the reduction of heat transfer due to mass injection. By extending the similar solutions of Kemp,[20] Hidalgo calculated the reduction in the heat transfer for laminar flow to be

$$\psi = \frac{q_j}{q} = 1 - 0.58\,\ell^{.04}\,\Delta^{-.18}\,B \tag{12}$$

where q_j and q are the heat transfer rates with and without injection, respectively, ℓ is the $\rho\mu$ ratio across the boundary layer without injection, Δ is Prandtl number and B is the blowing parameter defined as

$$B = \frac{\dot{m}_v}{q}(\Delta h)_o \tag{13}$$

The above equation was derived from numerical solutions of the boundary layer equations for dissociated air. There is also an effect due to the molecular weight of the injected gases as shown by the results of Baron. Hidalgo's correlation showed that the blowing parameter B should be multiplied by $(29/M)_m^{1/4}$ where M_m is the molecular weight of the injected material. Thus the transpiration factor for laminar flow becomes

$$\beta_L = 0.58\,\ell^{.04}\,\Delta^{-.18}\,(29/M)_m^{.25} \tag{14}$$

A correlation from the data of Baron for the case of $\ell = 1.0$ and no dissociation gave

$$\beta_L = 0.67\,(29/M)_m^{.25} \tag{15}$$

A rough check on the value of β_L under re-entry conditions from the ablation data of Georgiev [4] using Teflon gives a value of β_L of $0.60\left(\frac{29}{100}\right)^{1/4} = 0.44$. Thus the laminar transpiration factor is pretty well established both experimentally and theoretically.

For mass injection into a turbulent boundary layer, Hidalgo has found the following correlation equation to be in reasonable agreement

with the experimental data of Pappas.

$$\psi = \frac{q_j}{q} = 1 - 0.2(29/M)_m^{\alpha} B \qquad (16)$$

where α = 0.33 for $(29/M)_m \leq 1.0$

= 0.8 for $(29/M)_m \geq 1.0$

$$\text{or} \quad \beta_T = 0.2\,(29/M)_m^{\alpha} \qquad (17)$$

For the ablating materials of interest here, the 0.33 value of α is applicable because the vapor products have a greater average molecular weight than air.

The striking difference between the laminar and turbulent transpiration effect is shown in Fig. 4, where the calculated reduction in heat transfer rates with blowing is plotted for the case of Teflon. Based on the experimental data which leads to the values of α indicated above, the difference between laminar and turbulent ablation would be minimized if very light average molecular weight vapors were formed during the gasification process.

From the previous equations a general conclusion can be drawn about the choice of a material for turbulent ablation. Subliming materials or materials which achieve their high H_{eff} by having a large fraction vaporized (thereby depending strongly on blowing) may not be very good turbulent ablaters. A good turbulent ablater should get most of its effectiveness from a high heat of vaporization, i.e., the term $(f\,h_v)$.

As was seen from Eq. (9), a knowledge of the surface temperature during the ablation is necessary for the analysis of the experimental data. As previously discussed the surface temperature determines the value of CpTw and consequently the value of the hot wall heat transfer correction or the incident heat transfer on the specimen. The heat transfer rates measured in the calorimeter experiments must always be adjusted before they can be used due to the very high values of surface temperature of the ablating material.

The effective heat of ablation is heat transfer sensitive because of the effect of re-radiation of energy from the hot material surface into the plasma. For materials such as the quartz-like materials under investigation the surface is at a temperature of about 6000°R at pressures of five atmosphere and higher. This represents a re-radiation

rate of the order of 400 Btu/ft^2 sec (depending on the emissivity). Thus the value of H_{eff} would tend to go to infinity as the heat transfer rate to the hot wall tends to go to this value. This effect is very apparent in the case of the cylindrical surfaces of some re-entry vehicles. The maximum heat transfer rates here are barely greater than the re-radiation heat transfer rate due to the surface temperature of some of the presently used materials. Thus the ablation rates measured here have been very small and the resultant H_{eff} abnormally large.

In the turbulent pipe experiment the effect of re-radiation is eliminated and the values of H_{eff} are not heat transfer rate dependent. This is not precisely correct because the effective heat of ablation does depend on the body geometry or particle history in the boundary layer to some degree. However, this dependence is very weak for turbulent flow. This elimination of the re-radiation is caused by the fact that the gas is not very opaque in the conditions used in the experiments[21] and consequently the re-radiated energy goes through the transparent gas and is re-absorbed by another portion of the ablating surface. The absorption at the pipe surface is far greater than the absorption in the gas for each path length. Thus the turbulent pipe is an experiment in which the effect of radiation is eliminated and as such has added merit and significance.

Thus for the turbulent pipe experiment the effective heat of ablation can be written as

$$H_{eff}^{(0)} = C_p T_w + f h_v + f \beta (\Delta h)_0 = \frac{q}{\dot{m}_v} \tag{18}$$

From the above equation it can be seen that a measurement of H_{eff} or the rate of material ablation under known heat transfer conditions for a material which is known to sublime,[9] i.e., $f = 1$, leaves the transpiration factor or blowing effectiveness, β, as the only unknown quantity. This is effectively the same procedure as has been followed in laminar ablation experiments.

Teflon meets the requirement of ablating by direct sublimation into a vapor and is consequently suitable for measuring the blowing efficiency, β. Laminar experiments[4] yielded the result that

$$H_{eff}^{(0)} = 950 + .44 (\Delta h)_0 \tag{19}$$

To establish the value of the turbulent blowing efficiency β, the value of H_{eff} was measured at two different enthalpies. These measurements, see Fig. 5, produced a line with the equation

$$H_{eff}^{(o)} = (950) + (0.14)(\Delta h)_o \tag{20}$$

Analysis of the measured data indicates an uncertainty of plus (.05) for the value of the blowing efficiency, β , in the above equation.

The line for the above equation has been drawn through the lower enthalpy data and the known value of the heat of vaporization of Teflon[22]. The disagreement between the data points and the curve can probably be explained in terms of the prediction of the heat transfer rate change with diameter from the calorimetry. As can be seen from Fig. 6, Teflon ablates very smoothly but the calorimetry was performed for a step change in diameter. Thus the decrease in the exponent of the heat transfer rate variation with diameter change from 1.8 to .300 as indicated by the calorimetry data, Fig. 2, is probably not as strong for the Teflon experiment. This effect would tend to lower the high enthalpy data. The agreement of the present result with the value anticipated from the low speed, cold air results of Rubesin is quite gratifying in view of the shortcomings of the present experiments.

The agreement of the Teflon data with the turbulent blowing estimates and the close check between the turbulent heat transfer predictions and calorimeter data appears to verify our contention that the turbulent pipe experiment measures turbulent ablation. Figure 6 shows a photograph of a representative sample of Teflon as it appeared after the experiment. The samples were exposed for various lengths of time, and consequently the relative amounts of the apparent ablation on this picture are not significant. Two samples of Teflon are shown to indicate the uniformity of the diameter change over a large range of total ablation distance. This uniformity was not as good for flowing materials.

Some materials other than Teflon were tested under this program. The additional complexity of heat shield materials which do not sublime entirely but some fraction of whose products flow and leave the sample without fully evaporating does not effect this technique adversely. Examples of this type of material were refrasil laminates filled with a phenolic resin binder. Such materials ablate very uniformly and leave a thin but firm charred layer. There were no signs of flowing material, although analysis of the data shows that only 15% - 25% of the refrasil vaporized. The fraction vaporized was calculated using a blowing factor from Eq. (17) and an estimated molecular weight of the vapor of about 40 - 50. The latter was calculated by Shick[23] for the reaction

$$SiO_2 \rightleftharpoons SiO + \tfrac{1}{2} O_2 \tag{21}$$

and can also be estimated from the laminar data for quartz[7]. The result of substituting this molecular weight into Eq. (17) was a blowing parameter, β of 0.18. This value was used for analyzing the performance of refrasil and silica laminate-phenolic resin combinations. The fraction vaporized for these materials was calculated by substitution into

$$H_{eff}^{(o)} = C_p T_w + x h_{v(phenolic)} + (1-x) f h_{v(silica)} + [x + f(1-x)] \beta (\Delta h)_o \tag{22}$$

Opaque Quartz

This material was essentially pure hot pressed quartz made opaque by a material suspended in it. The material has a greyish appearance when cold. When the material is heated enough to flow, the impurity goes into solution and combines with the quartz to form a dark blue color. The physical properties of opaque quartz are apparently similar to those of clear quartz.

A characteristic difference between the ablation of this pure material and the composites of silica and plastic was that the flowing of the liquid layer was very much in evidence for opaque quartz. Apparently the fraction of this material which did not vaporize, i.e., 1 - f, flows along the pipe surface and out through the sonic nozzle. This was very evident from a thick coating of quartz found on the exit nozzle and in the supersonic expansion region aft of the sonic nozzle. This was opposed to the behavior of the other materials in which the silica which did not vaporize was injected into air stream and carried out through the nozzle.

The flowing quartz decreased the effective sonic throat size and raised the pressure of the tests. The oqaque quartz experiments were consequently performed in a range of pressure between 12 and 15 atmospheres, against an average pressure of 10 atmospheres for all the other materials. The models, when inspected after cooling, had a very rough inside surface, particularly at the downstream end. A characteristic wave pattern was noticeable. Whether this appearance is representative of the condition of the surface during ablation or is caused upon cooling is not known.

The performance of opaque quartz was estimated to Adams[1], as shown in Fig. 7. This estimate is based on the results of a large number of calculations by Hidalgo[8], using the Bethe-Adams theory[6] for different re-entry bodies. A region of zero pressure gradient on the fore cone of these bodies is used in the calculations to minimize the effect of geometry of Heff. The line on Fig. 7 is drawn roughly through the mean of the values calculated in this manner.

Nylon Phenolic

The ablation of nylon phenolic is a more complex process than the materials considered so far, involving not only melting and evaporation but also pyrolysis of the plastic forming many different chemical species and combustion. These processes finally leave a charred layer which has been completely stripped of its nylon and which is extremely hot and brittle. This char residue is due completely to the decomposition of the phenolic resin[5].

The appearance of the nylon phenolic specimen after these experiments is quite characteristic and completely different from the other materials tested. There is no evidence of any flow of nylon although this has been observed experimentally in high speed motion pictures of stagnation point ablation in a supersonic, low pressure arc wind tunnel. The pipe had many deep longitudinal gouges up to 1/4 inch deep. The surface was quite irregular due to these gouges, as can be seen on the photograph, Fig. 6. The charred layer was extremely brittle and in many places broke off during handling.

Yet despite this poor physical appearance nylon phenolic exhibited excellent effective heat of ablation values in these tests. The analysis of the nylon phenolic ablation data was complicated by the absence of a reliable estimate of the surface temperature of the char layer during ablation. From laminar experiments* the effective heat of ablation was found to be

$$H_{eff}^{(o)} = 1000 + 0.52\,(\Delta h)_o \tag{23}$$

Steg[5] gave an estimate due to Scala which was

$$H_{eff}^{(o)} = 1500 + 0.50\,(\Delta h)_o \tag{24}$$

Equations (23) and (24) indicate that the products of the gasification of the nylon and the phenolic resin have an average molecular weight of about 50. In the above mentioned experiments the surface temperatures were measured to be 5000°R. These experiments were performed at a

* Unpublished experiments by Georgiev and Adams at Avco-Everett Research Laboratory.

fraction of an atmosphere pressure. Due to the great dependence of the numerical results on the surface temperature, the interpretation of these experiments is somewhat speculative where surface temperature is not well known.

One way to explain the experimental values of H_{eff} for nylon phenolic is to assume that the charred layer achieves a much greater temperature than was measured in the laminar experiment. Some spectrographic measurements have indicated surface temperatures greater than 5800°R for nylon phenolic during ablation. From the ablation measurements H_{eff}^{g} can be calculated for any assumed surface temperature for the enthalpy levels tested.

More accurate determination of the behavior of ablating nylon phenolic will need a good surface temperature measurement during ablation. However, from the present experiments it can be concluded that the surface temperature of the char layer is probably very high in the vicinity of 6000°R. These data, together with the appearance of the char layer after the experiment, lend emphasis to the important position of the char layer in the behavior of nylon phenolic. In order to perform properly in turbulent flow, nylon phenolic apparently needs a very high surface temperature. This can only be achieved by the presence of a complete and continuous char layer. If the char layer is broken or removed even locally, then the ablation rate increases by a large factor until a full char layer is reestablished. This may be a speculative explanation of the gouges on the inside of the model.

The extremely fragile state of the char layer leads to another reservation about the use of this data in projecting flight performance. The present experiments were performed at approximately (within a factor of two) the proper pressure, enthalpy and heat transfer rate for simulating ballistic missile re-entry. However, the conditions are quite different with respect to velocity and consequently also shear. The shear on the fore cone of the re-entering nose cone is approximately 20 times higher. Thus the apparent ability of the char layer to withstand the experimental conditions of the pipe test does not guarantee its equivalent behavior during re-entry. Unfortunately although experiments were performed at higher pressures, higher shears were not possible in these experiments and consequently no additional light was shed in this regard.

Conclusion

The data and techniques described in this paper have led to the following results:

(1) Ablation tests in a turbulent pipe flow have led to a measurement of the turbulent transpiration parameter.

(2) A number of interesting heat shield materials have been evaluated.

(3) The accuracy of the data produced by the experiments described is limited because of limitations on presently available arc plasma generator. The large corrections which were necessary in the evaluation of the data would be minimized if a larger power input were available.

The experiments described in this paper have since been confirmed and extended in the Ten-Megawatt Arc Facility[9] at AVCO/RAD[24]. In this facility the conditions shown in Fig. 2 have been achieved. That turbulent boundary layer flow has been achieved can be shown by the calorimetric measurements shown in Fig. 10. Utilizing this facility, measurements were made on Teflon over a large range of conditions. These measurements confirm the relationship inferred from the sparse data of this investigation, as shown in Fig. 11.

Acknowledgment

The authors wish to acknowledge the assistance of Mr. O. K. Salmassy of the Research and Advanced Development Division for his work in supervising the fabrication of the ablation models used in the present investigation. The experiments were performed by Mr. W. Stark of the Avco-Everett Research Laboratory. The authors are also indebted to Dr. M. C. Adams for the many stimulating discussions during the progress of the work, and to Mr. C. Bond of AVCO/RAD for making available the results of his experiments in the Ten-Megawatt Arc Facility.

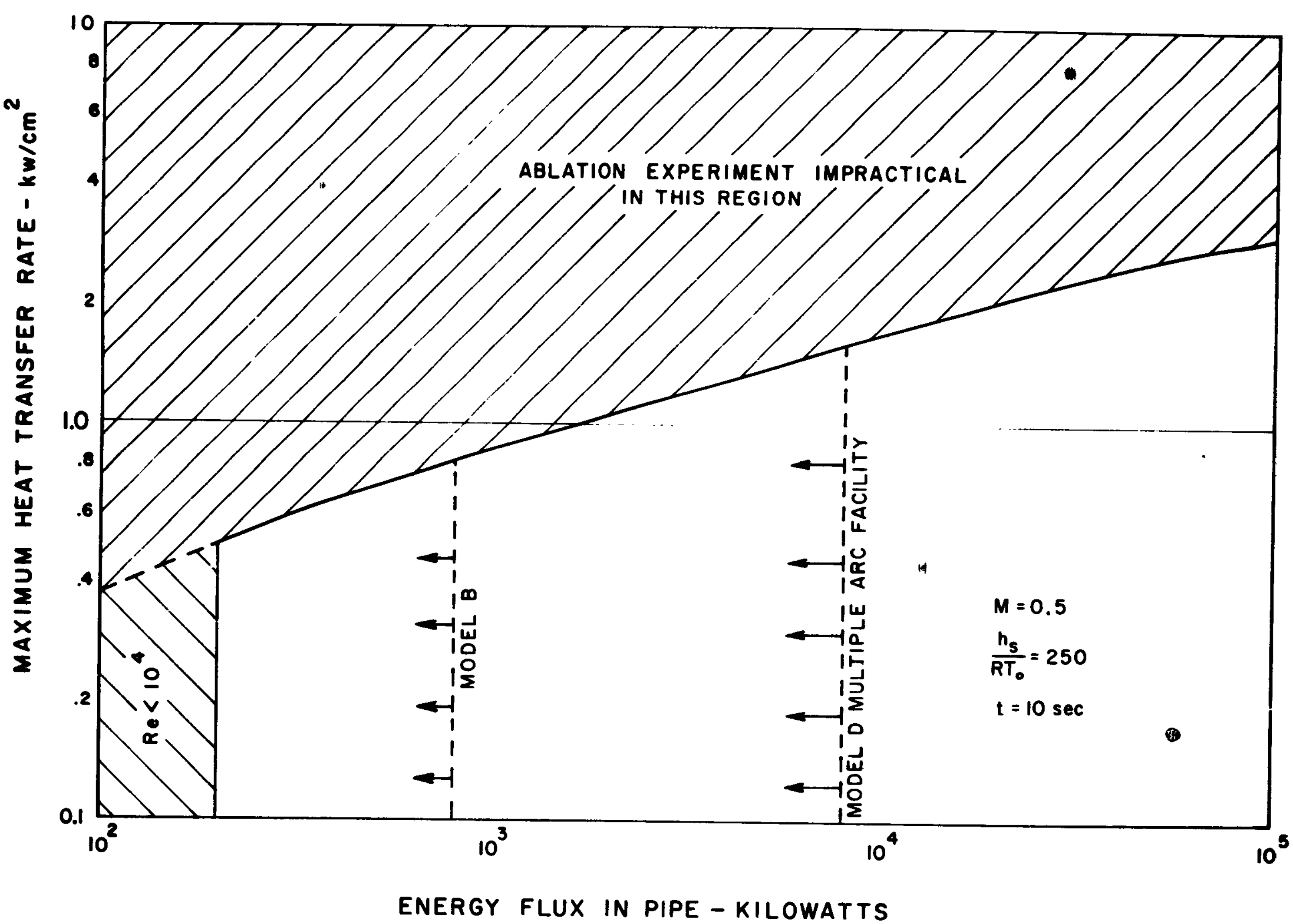

Fig. 1 Limitations of Turbulent Pipe Experiment.

2062

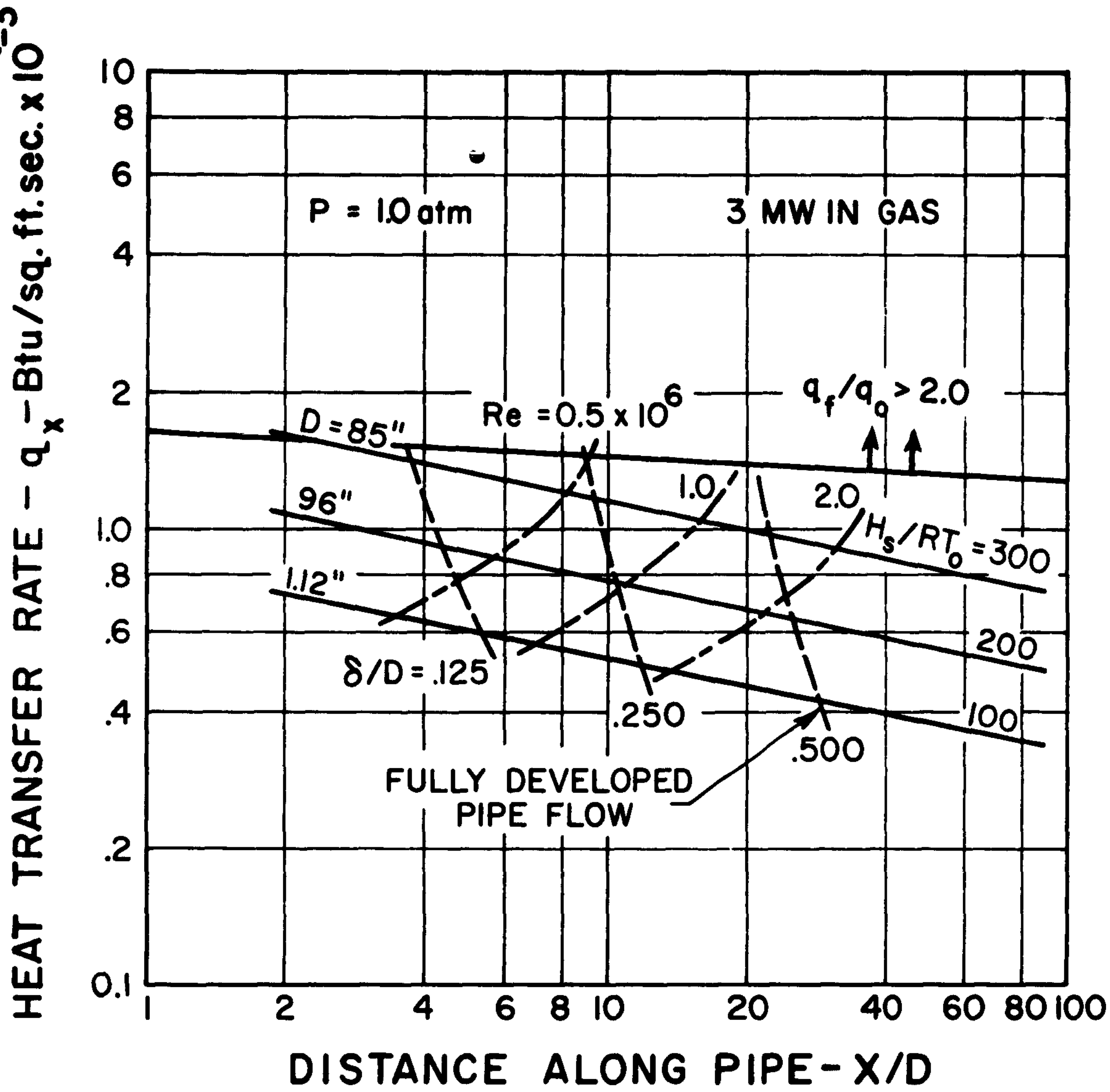

Fig. 2 Conditions achievable in a pipe flow experiment with arc delivering plasma at 10 atmospheres and with 3.0 MW of power in the air.

3004

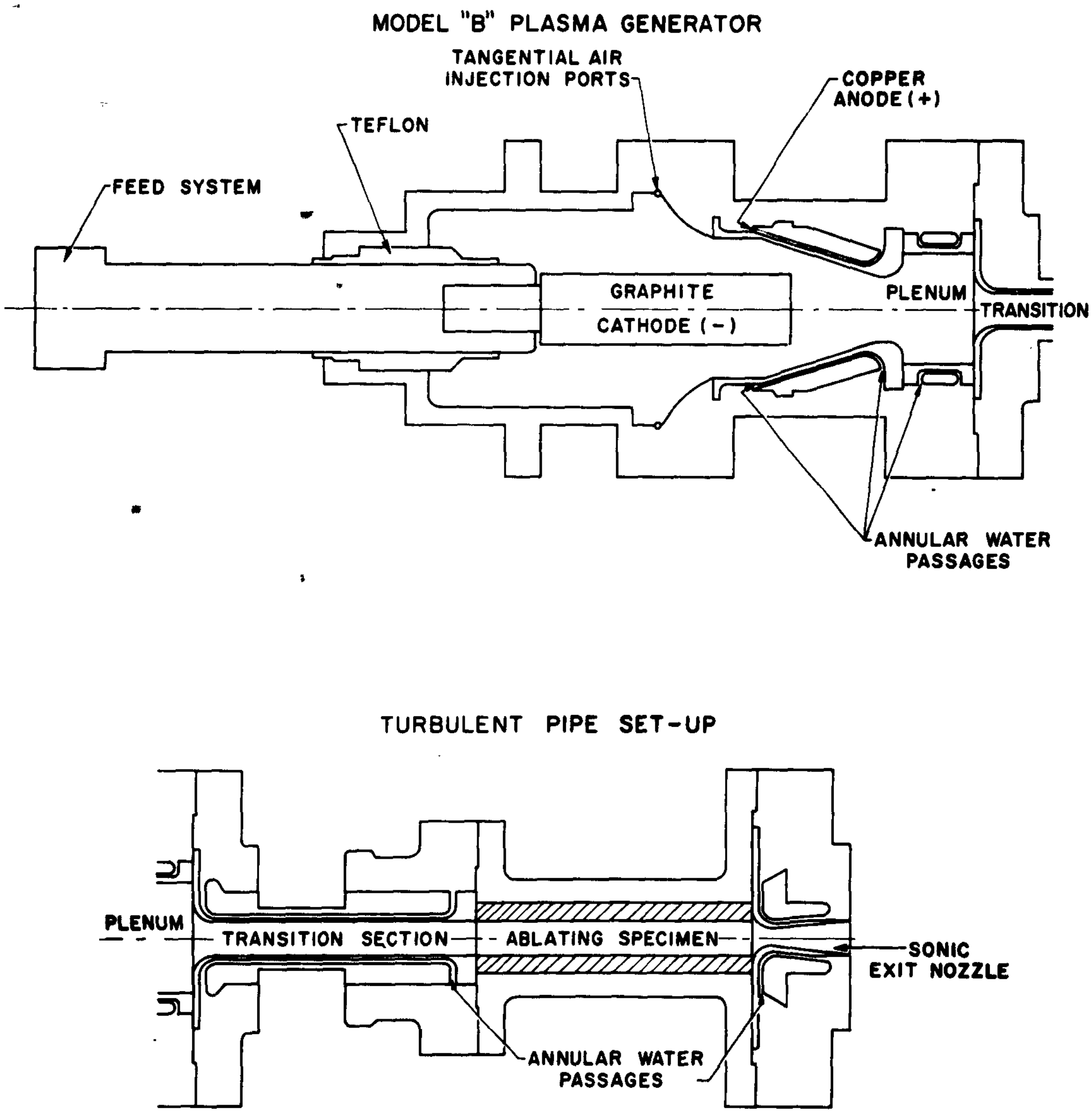

Fig. 3 Schematic Drawing of Experimental Equipment.

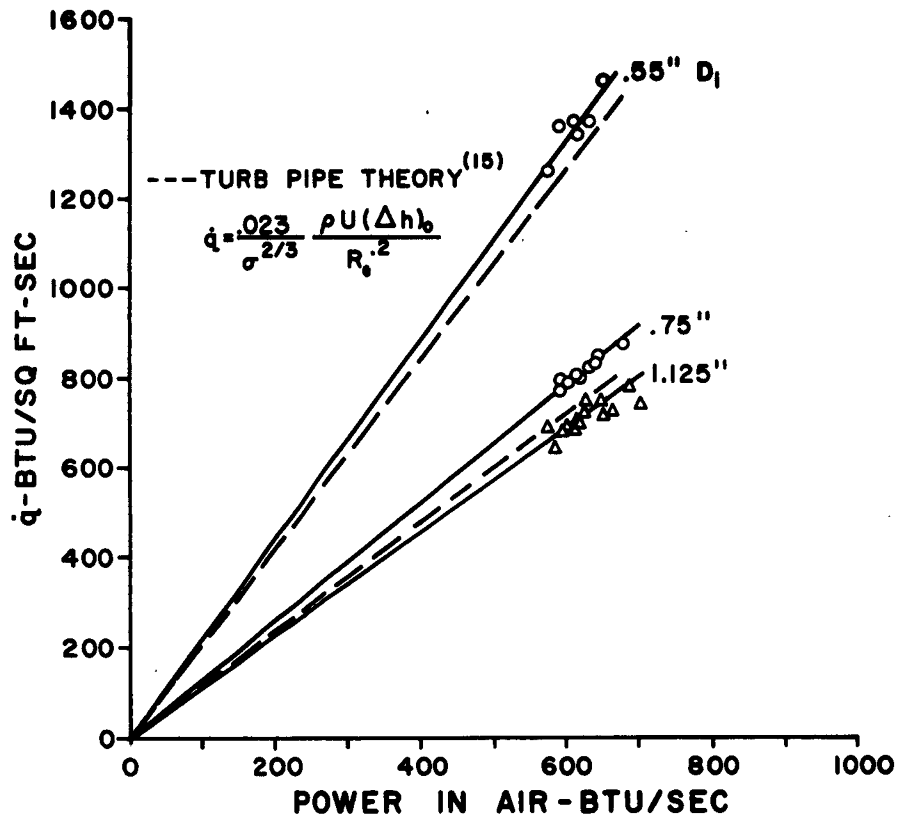

Fig. 4 **Results of Calorimetry Measurements.**

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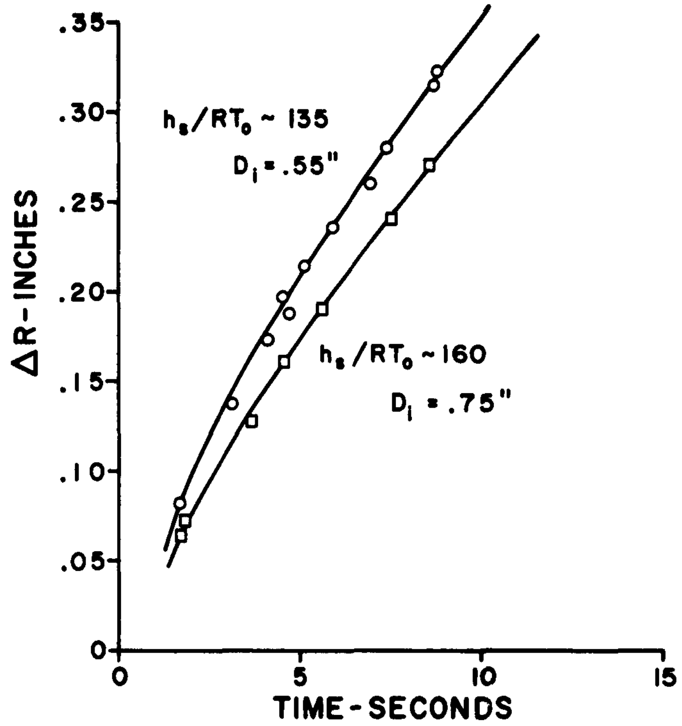

Fig. 5 Diameter Change of Teflon.

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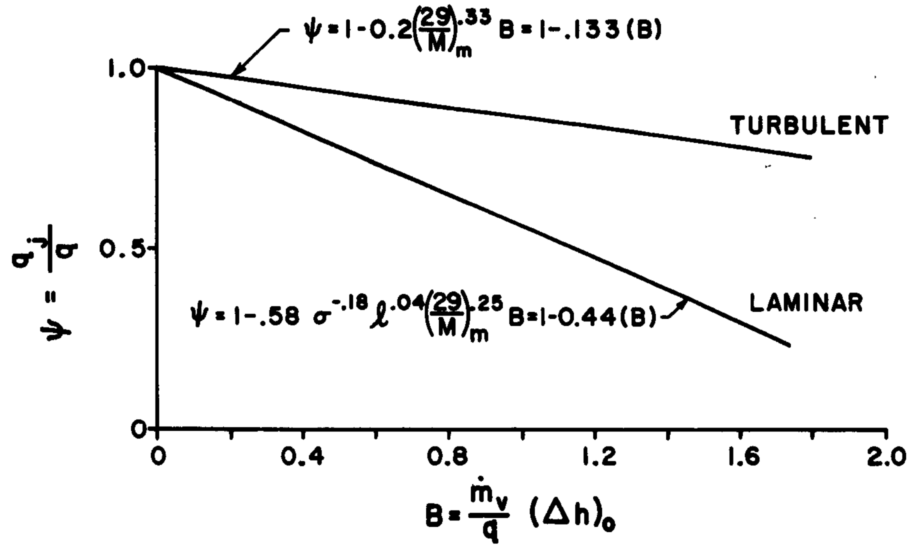

Fig. 6 Effect of Mass Injection Due to Ablating Teflon (Mol. Wt.$\sim$ 100).

3231

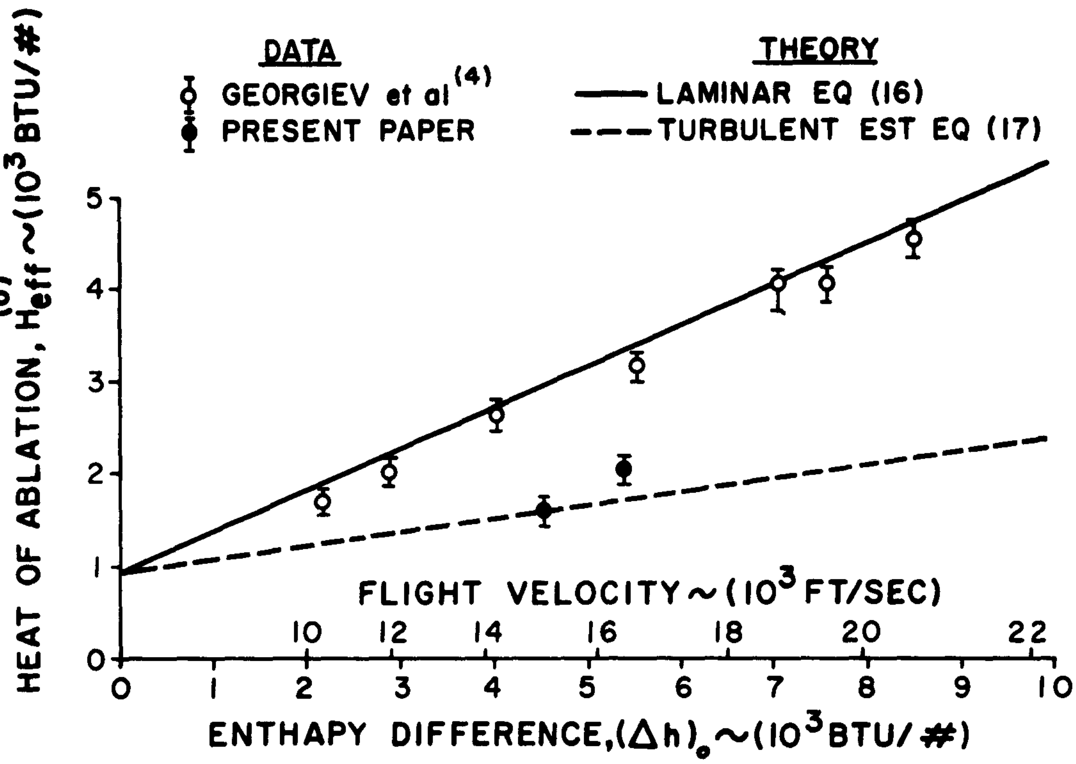

Fig. 7 Teflon Ablation.

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Fig. 8 Samples from Turbulent Pipe Test.

5667

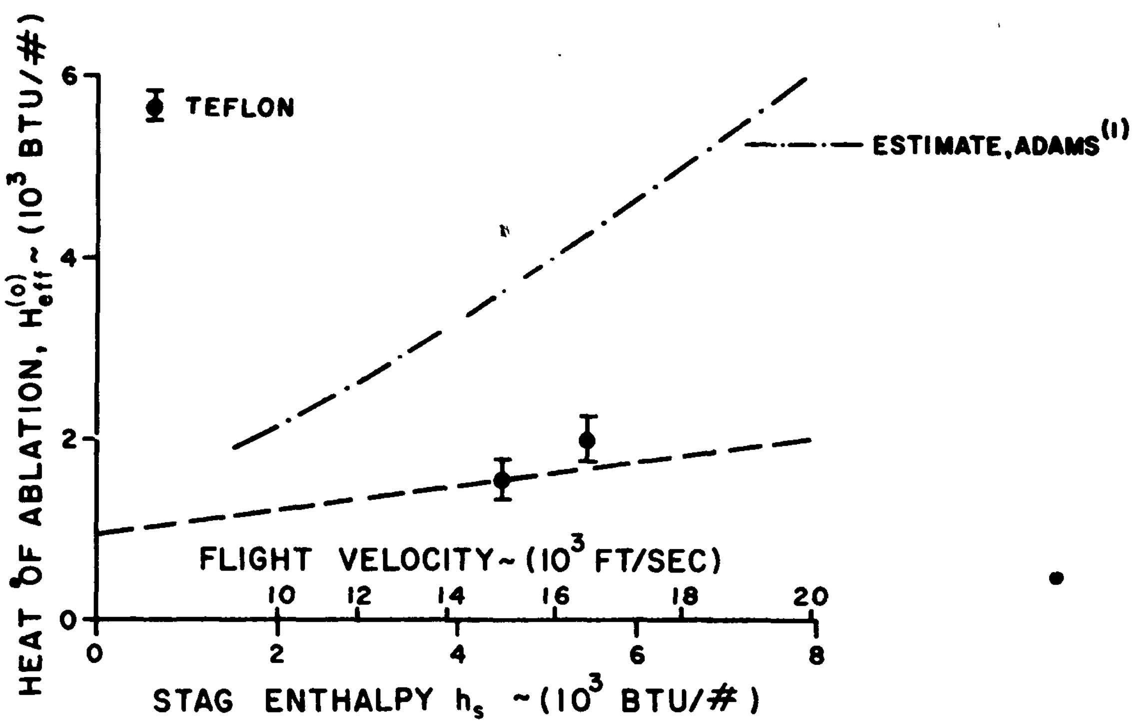

Fig. 9 Summary of Turbulent Ablation Data.

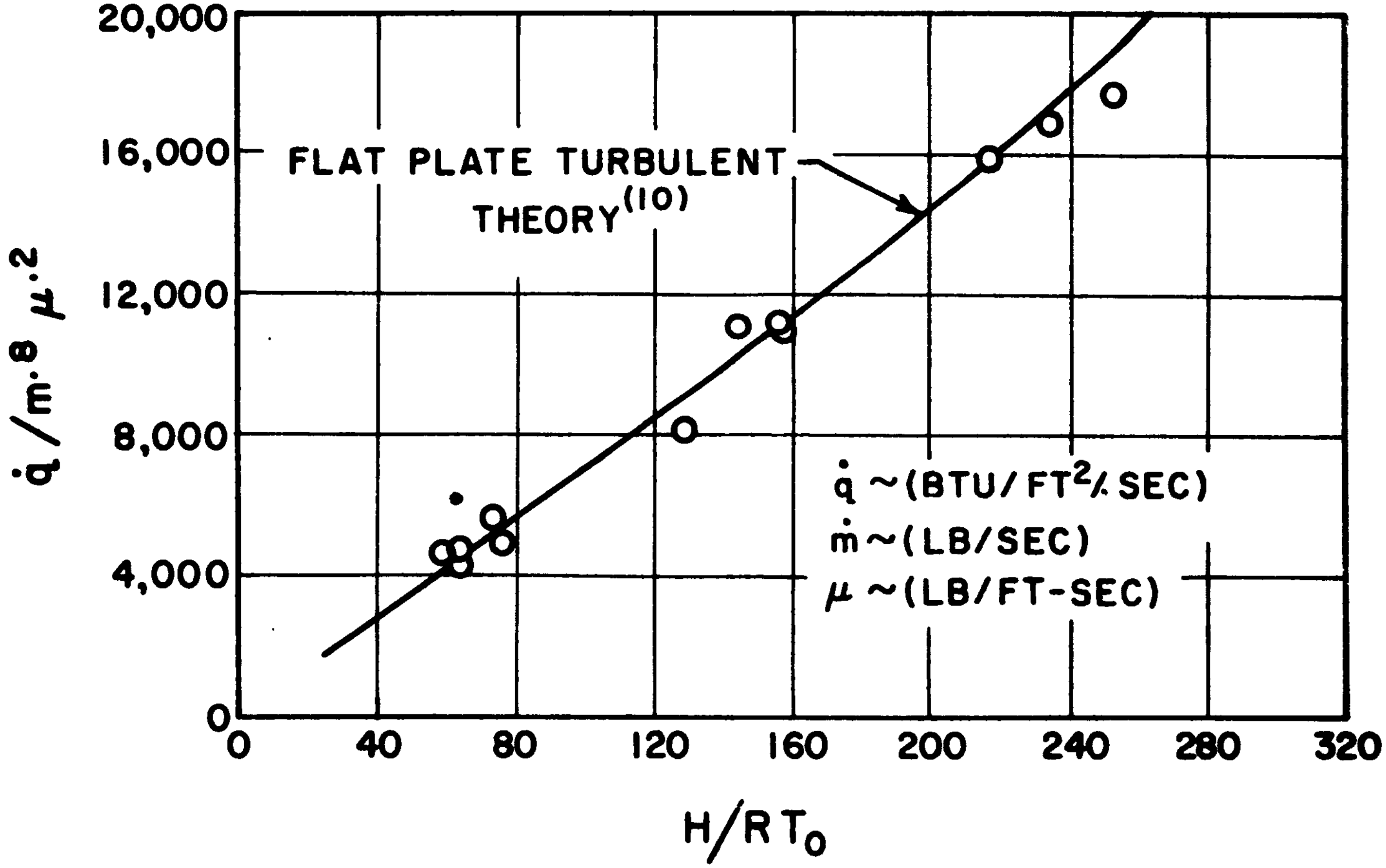

Fig. 10 Calibration Curve
1.25" Pipe, 10 MW Arc Facility
(From Ref. 24)

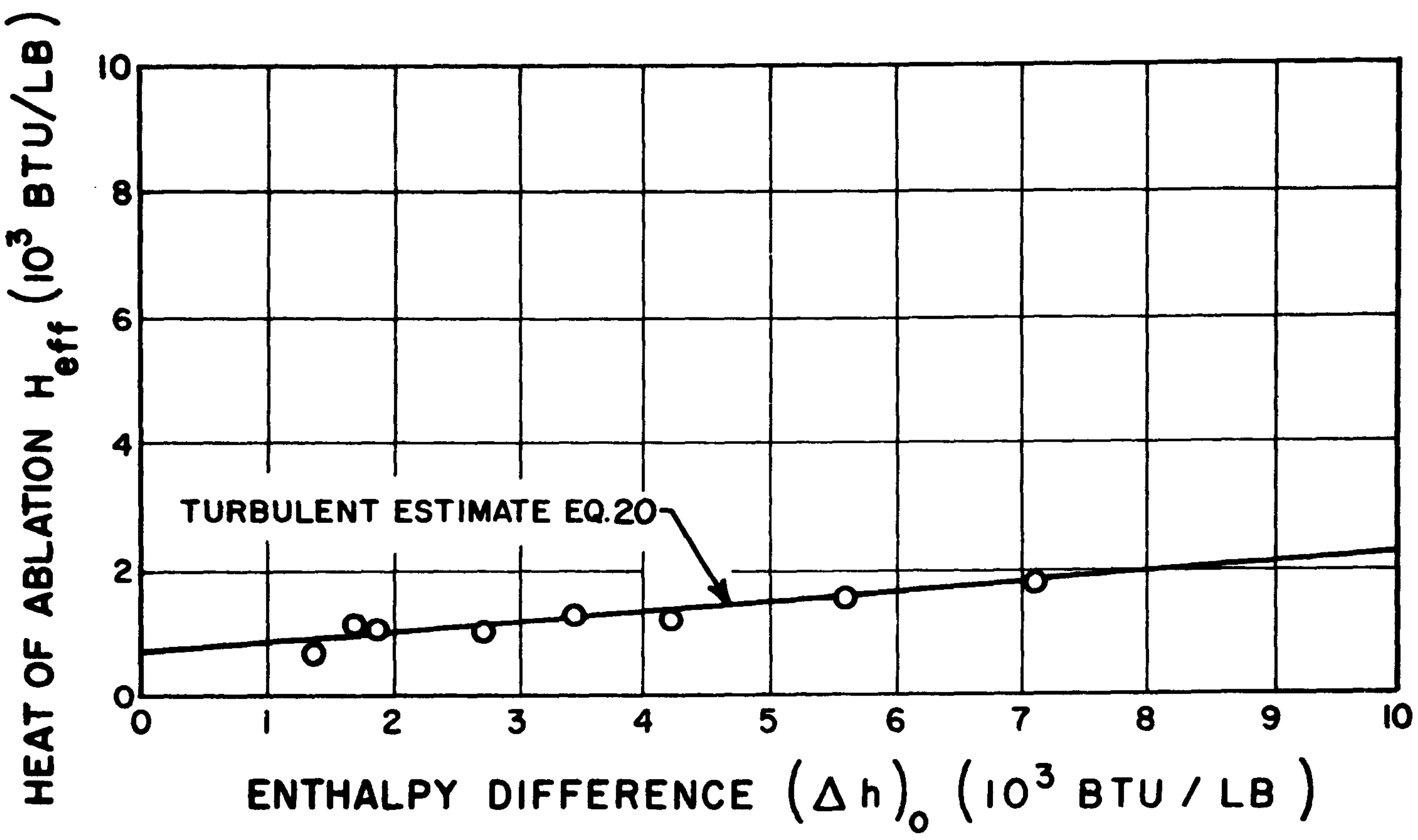

Fig. 11 Teflon Ablation Results
10 MW Arc Facility
(From Ref. 24)

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Avco-Everett Research Laboratory, Everett, Massachusetts
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Unclassified report

Turbulent pipe flow experiments have been obtained under conditions which were similar to the peak heating conditions of high performance ballistic missiles (approximately 20 percent lower enthalpy and one-half the stagnation pressure). Several typical ablation materials were investigated to determine their performance under these conditions. It was possible to determine the effective heat of ablation for each of these materials and to experimentally demonstrate the difference between the ablative process in laminar and turbulent flow. In this paper the Teflon experiments are discussed in detail to demonstrate the validity and power of this technique.

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2. Flow, Laminar - Ablation.
3. Flow, Turbulent - Ablation.
4. Nose Cones - Ablation.
5. Nose Cones - Re-entry.

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III. Offenhartz, E.
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